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ABSTRACT

Robots are mechanical devices that can be programmed to perform some task of manipulation or locomotion under automatic control. This paper discusses: (1) early developments of the robotics industry in the United States; (2) the present structure of the industry; (3) noneconomic factors related to the use of robots; (4) labor considerations (noting how productivity improvements resulting from the use of robots and related technologies can affect labor and pointing out a number of education and training issues raised by robotics in robot installation, programming, and maintenance); (5) productivity and capital formation (considering whether there is adequate capital to fund the modernization of industrial plants for use of automation technology, to fund the construction and expansion of plants to produce robots in quantities necessary to have a significant economic impact, and to fund entrepreneurs who wish to develop new types of robots for new applications); (6) robot applications, focusing on spot welding, arc welding, spray painting and coating, and on advantages offered by industrial robots in painting), machine loading and unloading, machining, transferring, and assembling; and (7) prospects for the future. (JN)

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INDUSTRIAL ROBOTS

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DEFINITION AND INTRODUCTION

A robot is a mechanical device that can be programmed to perform some task of manipulation or locomotion under automatic control. Today robots are still on the threshold of research and development. However, industrial robots are available in a wide range of configurations and capabilities, from simple "pick-and-place" devices to computer-directed, servo-controlled, point-to-point, and continuous-path units. Programmable controls, memory systems and up to seven articulations give a high degree of flexibility and adaptability to many tasks involving manipulation of objects and tools.[1]

When the actual tasks that a robot can perform are studied in a real factory world, they boil down to moving parts in simple combinations of straight lines and rotations. Each task requires a different combination of motions, and each task requires different travel distances and imposes different weight loads on the robot. Generating such motions with jointed arms requires large numbers of joints.

While robots vary widely in shape, size, and capabilities, they generally consist of three basic components: the manipulator, the control, and the power supply that drives the manipulator. Manipulators are the mechanical devices that do the work and provide the dexterity by pneumatically, hydraulically, or electrically driven jointed mechanisms that can perform as many as seven independent coordinate motions.[2]

EARLY DEVELOPMENTS IN U.S. ROBOTICS INDUSTRY

During the 1940's and 50's, development work was done on most of the elements of industrial robots. U.S. patents were issued for work on articulated arms, remote materials handling, manual "teachability" (in connection with early paint spraying machines), and programmable controls (both punched tape and microprocessor-based types). By the mid-fifties George Devol was citing many of these patents in his own work on a Programmed Article Transfer System which was patented in 1961 and generally recognized as the first programmable industrial robot.[3]

The Devol patents were bought as a package by Consolidated Diesel Engine Company (Condec) which set up a subsidiary, Unimation, Inc. to exploit them. The first servo-controlled, continuous-path Unimate robot was sold to General Motors in 1961. American Machine and Foundry Corporation (AMF) began to market its non-servo-controlled, point-to-point Versatran robots shortly thereafter.[4]

These early robots were unproven and risky. They were expensive (in the context of the times), costing an average of $25,000 each, and about $4/hour to operate. Their control and feedback technology limited the application of robots to only a few simple jobs. As a result, there were only about two hundred robots in the U.S. by 1970, used primarily in jobs that were too hazardous or boring for humans.

This situation changed during the 1970's. Productivity growth in manufacturing slowed at the same time wage rates in-

creased rapidly. The cost of many manufacturing inputs increased as well, due to successive "oil shocks." Manufacturing managers intensified the search for cost-control methods.[5]

The control, flexibility and manipulative capabilities of robots were being improved at the same time. Cincinnati Milacron had developed a system to control several NC machine tools directly from a central computer (thus by-passing tape readers) in the mid 1950's. Building on this experience, Milacron introduced the first minicomputer-controlled robot, the T3 in 1974. Minicomputers were replaced by microprocessor controls during the late 1970's. As CAD and AS/RS systems were developed and refined, their links to CAM were explored, and computer integrated manufacturing (CIM) became a real possibility.

In response to these developments (economic and technological) robot use grew somewhat during the late 1970's. Yet by 1978, the Robot Institute of America (RIA-the principal U.S. trade association for robots) consisted of just ten manufacturers, three accessory makers, twenty-five users, and three research organizations. In that year, some six hundred and fifty robots were sold (for a dollar value of about $46 Million), raising the total of robots installed to approximately 2,500.[6]

PRESENT STRUCTURE

Interest in AMES products has grown rapidly since 1978. The increase in actual sales and in the use of robots has been less spectacular, but still significant. It is estimated that 2,100 robots were sold in 1981 (for a total value of $155 Million),

increasing the base of robots installed to over 5,000. During the past five years of rapid growth, the number of firms supplying robots has grown from a dozen to approximately fifty. During 1982 a half-dozen firms entered (or announced their intention to enter) the U.S. market as suppliers and/or manufacturers of AMES.[7]

This dynamic state of the producer industry is complicated by restrictions on capital spending (caused by the recession) among many potential robot users. A large portion (up to 50%) of the rapid market expansion since 1978 was due to large orders for robots placed by the automobile makers. Such an order volume may not be sustained if the hard-hit automobile sector puts off capital spending in order to weather the recession. This will only delay the growth of some AMES producers; others, especially smaller firms and start-ups less able to absorb losses, will drop out of the market.[8]

At present, two firms account for nearly 75% of total U.S. robot sales. Unimation's 1981 sales of $68 Million (43% market share) represented over 17% of parent Condec's corporate sales. Cincinnati Milacron, the largest U.S. machine tool manufacturer, had robot sales of $50 Million in 1981 (32% market share), representing only about 5% of total corporate revenue.

In 1981, the top eight AMES producers accounted for 97% of an estimated $155 Million in U.S. sales. Leaving aside the two industry giants described above, these firms had sales of between $3-9 Million a piece. In order of declining market share, they are: ASEA (U.S. subsidiary of the pioneering Swedish firm);

Prab Robots (which purchased AMF's Versatron robot line); DeVilbiss (developer of some early fixed-sequence paint spraying robots, now licensing technology from Norway's Trallfa); Copperweld Robotics (created by Copperweld Corporation's purchase of established robotmaker Autoplace); Automatix (largely a systems integrator, stressing control and sensory technology); and Nordson (a manufacturer of surface coating equipment now licensing robot technology from Italy's Basfer to round out its product line).[9]

The total U.S. market for AMES should reach $2-4 Billion by 1990. Several very large firms have entered the market (Bendix, General Electric, General Motors, IBM, Westinghouse) or may soon enter (Digital Equipment Corp., Texas Instruments, Textron, United Technologies) in anticipation of the projected growth. The entry of these firms will intensify several trends as the industry matures. The end-user market will become much more diversified. This is already happening as potential users become aware of robotic applications in their industries, and as current robot producers struggle to expand sales in spite of slumping orders from the auto industry. Some of the new entrants will use large numbers of robots internally. All of them have a strong sales presence in other industries, enabling them to effectively broaden the user base.[10]

The entry of large firms will also accelerate the trend towards functional diversity in robot applications. Up to 35% of all robots sold in 1980 were used for automobile spot welding. Functional diversity is increasing not only in response to the

"pull" of a broader base of users, but also because large firms can "push" new technology to capitalize on some internal strength (e.g., in a related product, a proprietary innovation, or in engineering a particular application).

IBM, for example, first began R & D[11] on robotics in 1972 in order to find new applications for computers on the factory floor. The robot arm of its new 7535 Manufacturing System (primarily for light assembly) is made by Sankyo Seiki in Japan. The $28,000 robot is controlled by a $5,000 IBM personal computer (and software) reflecting IBM's traditional strength.[12]

As functional applications become increasingly diverse, the producer industry is likely to respond by becoming more segmented. In the area of surface coating, for example, De Vilbiss has been clearly dominant, based on its previous experience in the field. Some firms may choose to limit themselves to a certain market segment (according to application level of technology, geographical area, price, etc.) as a conscious strategy to establish a defensible niche in the face of increasing competition. Mobot Corporation, for example, has concentrated on selling non-programmable robots to gain a small but relatively secure share (1%) of the U.S. market.

Finding a secure niche will be difficult in the long run as the number of competitors increases in each. De Vilbiss has been joined by Nordson, Binks, Graco, Cybotech, Thermwood, General Electric and General Motors in the area of surface coating robots. There are at least nine U.S. firms competing in the field of arc-welding robots, a rapidly growing application that now

license by U.S. firms, many Japanese robots are priced lower than comparable domestic models.[16]

Falling prices will stabilize over time and some AMES products for certain well-established applications will behave like commodities, as already reflected in the price-performance ratios for auto body spot welding robots. Continued technological innovation in robot material, controls, drive systems, sensors, architecture, and especially software, together with price, will be the bases of competition through the 1980's.

PRICE RANGE FOR ROBOTS[17]

COUNTRY	PRICE RANGE (US $)
United States	10,000 - 150,000
Japan	6,825 - 100,000
Europe	
West Germany	13,200 - 123,200
United Kingdom	17,400 - 110,400
Sweden	8,860 - 90,000
Norway	8,519 - 85,175
France	4,000 - 160,000
Italy	10,000 - 150,000

In most cases, increased productivity results from the robotic ability to maintain a constant pace throughout the entire workshift, rather than the robotic ability to perform tasks faster than a person. In some cases, a person can outperform a robot in the speed with which a task is completed, especially in some complex manipulative tasks. However, a person usually cannot maintain this performance level for an entire shift because of fatigue. Generally, robotic technology provides a tireless worker and increased productivity by maintaining a constant rate of production for extended periods of time. The average cycle time for parts tends to be lower for robots. The result is that more parts are produced per shift, and this increased productivity represents an economic gain.[18]

These advantages are realized through the consistent operation of the robot. Once an optimum procedure is defined and programmed into the robot for a particular task, that task will be consistently performed in the optimum manner everytime. The result is fewer bad parts that have to be scrapped, less material waste, and measureable economic gains.[19]

Robots are frequently used to perform operations that are potentially hazardous to human workers, usually to comply with safety regulations. These hazardous operations include press loading and unloading and working in toxic atmospheres or extremes of ambient temperatures. Improved safety can result in reduced operating costs and provide some economic justification. However,

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a robotic solution to safety problems may not always be economically desirable, and wisdom dictates that alternatives also be investigated.

Robots can be used to perform some undesirable tasks, and the result is additional cost savings. If ignored, workers' complaints about poor working conditions (i.e., excessive noise, dust, fumes, heat, dirt, heavy loads, fast pace, or monotony) can lead to work stoppages or slowdown, uncompleted operations, poor workmanship, high labor turnover, absenteeism, grievances, or sabotage, and can result in higher-than-normal operating costs. Compensation may require overtime to make up production losses, rework and repair, and expenses for processing grievances, hiring replacement personnel, and training new workers. In many cases, robotics is a cost-effective solution.[20]

A robot may be introduced for the advancement of technology. In such applications, one or a limited number of robots may be installed for developmental purposes. The intent here is to gain knowledge and expertise required to implement similar robotic applications in an actual production setting where economic benefits are more direct. Economic returns are usually realized in the follow on production applications. In fact, the costs of a developmental implementation are often factored into the cost of the follow on production application.[21]

Industrial robots are adaptable. Whether programmable or not, most have a degree of adaptability that allows them to be moved around or used in different types of tasks, thereby increasing their usefulness and potential return on investments.

However, few managers will accept the adaptability of a robot as a justification for installing one without a plan for how it can and will be used in different applications. Adaptability may be a possibility but should not be used as a justification factor unless a serious implementation plan is established. Usually the feasibility of adapting to other applications will diminish as development progresses owing to the enhancements specifically designed for the primary application (e.g., tooling, facilities layout). Adaptability is an intangible asset that may become useful in a contingency situation.[22]

Enhancement of competitive position has both direct and indirect economic implications. Direct benefits are obvious. Lower production costs resulting from the use of robots give a manufacturer a pricing advantage over his or her competitors. The inherent flexibility of robot manufacturing systems indirectly affects the economics. Shifting market demands are easily met by increasing or decreasing production rates on various products without changing the size of the workforce. New products can also be introduced quickly and easily, often with little change to the production facilities.

Occasionally, a robotic implmentation may be made on the basis of management direction. This alone is a poor justification for implementation, especially if the determination is not based on economic considerations. Projects based solely on this type of impetus tend to have a low success rate. Efforts to comply with a directive may result in careless choice of robot or application. The application may become more complex than

first anticipated, or the robot may not have the necessary capabilities to perform the tasks. Aside from the obvious waste of capital, a bad experience may discourage management from further attempts to implement robotic technology, even when other potentially successful applications may exist.[23]

LABOR

Unemployment is an issue that is constantly raised in discussions about the social impact of robots, but one that seems in this context not to be well understood as yet or even to have been widely studied by labor economists in the United States.[24]

Productivity improvements resulting from the use of robotics and related technologies can affect labor in a number of ways. These effects depend on factors such as the following:[25]

- The effects of new technology on the relative proportion of machinery to workers (the capital-labor ratio) in a given industry.
- The extent of change in prices and production volumes for U.S. firms once the new technology is in use.
- The supply of qualified workers with specific job skills in a given industry.

U.S. employment in a given industry may fall because of productivity improvements, which, by definition, enable fewer workers to produce a given volume of product. U.S. employment in a given

industry may remain constant or rise, however, if productivity improvements are combined with increases in production volume. Effective labor compensation may rise or fall if productivity improvments lead to shorter work weeks or new product prices or both depending in large part on production volume and profitability. Finally, average wage levels will change with changes in the necessary mix of worker skills resulting from the implementation of robotics and related technologies.[26]

Definitions of unemployment, like those of productivity, require distinctions between short-term and persistent job loss, or between true unemployment (job loss) and displacement (job shift).

For some time, most experts in the United States have argued that more jobs are created by new technology than are eliminated. However, if these jobs are in different industries and/or require different skills, the effect on an individual who would be replaced by automation could be traumatic. Currently, it is very difficult to identify individuals who have lost their jobs due to the introduction of a robot. In general, if they have been replaced in a union organization, they will bump someone else, which ripples through the job structure.

Production and servicing of robots and related technologies will create new jobs. The number of jobs created and the rate at which they appear will depend both on the growth rate of the robot industry and on the degree to which robot manufacture and repair are themselves automated.

Additionally, the effects of modern microelectronics will

be to lower cost, improve performance, and widen the availability of automation technology substantially. The negative impact on employment that, in the past, had been small enough to be insignificant or undetectable may be much larger in the future.[27]

To assess the effects of automation on future employment levels, a baseline must be established against which job loss or gain can be measured. This baseline could be a simple extrapolation of current trends; but it also may need to be adjusted to reflect two other effects:[28]

- Virtual employment--domestic jobs that were not explicitly eliminated, but that would have existed were robots not installed.
- Virtual unemployment--domestic jobs that would have been lost if the plant had not responded to domestic and international competition by automating.

As is the case with productivity, it is difficult to attribute employment effects to any single component of an entire range of improvements in the manufacturing process, in this case robotics. Any examination of the effects of robots on jobs would need to consider, at least in part, a much broader context of automation technology.

There seems to be two principal sets of questions concerning unemployment. These questions are different in their focus, in their implications, and in the data collection necessary to analyze them:

1) Will the United States experience a long-term rise in the real unemployment rate due to the introduction of robotics and other automation? If so, will these effects be differentially severe by geographical location, social class, education level, race, sex, or other characteristics? What might be the employment penalty of not automating.

2) Will the use of robots create displacement effects over the next decade? In what ways will these effects be specific to particular industry classes, geographical locations, or types of jobs? How will they affect labor/management negotiations?[29]

Quality of working environment is another issue that has been addressed. If robots are employed principally for jobs that are unpleasant or dangerous and if the new jobs created by robotics are better, the quality of work life will improve. Productivity increases may also, in the longer term, result in a shorter, more flexibly scheduled work weeks.

New forms of computer-based automation may in many cases relieve job boredom and resulting worker dissatisfaction that many management experts have been concerned with. Workers may be able to make use of more complex skills and perform a greater variety of tasks. For instance, they may be able to follow the assembly of a product from beginning to end and assume greater individual responsibility for the quality of the result.

The human working environment can also be improved by segregating processes that create hazardous working conditions (such as heat or exposure to chemicals) from the section of the factory occupied by humans, and staffing them with robots. Furthermore, equipping a worker with a robot helper for strenuous activities not only eases job stress but also opens up employment opportunities to those who have physical handicaps or other limitations.

Whether these benefits are realized depends, in part, on the particular ways in which industry uses the technology. Many labor experts are concerned that some uses of robots will produce effects on the working environment that will not be so salutary. For example, some argue that one long-term effect of robotics may be to "deskill" labor, requiring less ability on the part of humans as they are incorporated into a mechanized environment.[30]

Some labor experts and others have also expressed concern that automation provides increased opportunities for employer surveillance of employees. Some unions also fear that automation could be used by employers to "down grade" jobs that require working with automated systems, or that robots might be targeted to replace unionized jobs first.

A number of education and training issues are raised by robotics in robot installation, programming, and maintenance.

There is a shortage of trained technical experts in the field of robotics. If there is to be any significant expansion in the place of automation including robotics, many more computer scientists, engineers, software programmers, and technicians will be needed in the next decade.[31]

A shortage already exists in many fields of engineering and science. It seems to be particularly critical in areas of computer software design and programming. Hence, the issue is not peculiarly unique to robotics technology, at least in the case of very highly skilled jobs.

At the same time, the use of robots has already created some new technical jobs. A few programs hae been started at the community college level to train workers in robot installation, programming and maintenance.[32]

There is a need for a more technologically literate workforce, one that has a basic understanding of technology and mathematics. Improved technological literacy would provide the following benefits:

1) To the extent that workers would be expected to instruct, oversee the protection of, or repair robot units, they would need some basic understanding of computers and systems, both mechanical and electrical.
2) A technologically literate workforce would be less likely to resist the introduction of robots and other automation technology.
3) A knowledgeable, technologically skilled worker would be easier to retrain for some other job, somewhere else in the plant.[33]

If the introduction of robotics is not to result in unemployment, a program of retraining displaced workers to take on new jobs will be necessary. Retraining also will be required for those workers who remain, for their existing jobs will change in form and function even if their job titles remain the same.[34]

PRODUCTIVITY AND CAPITAL FORMATION

Some experts warn about making simplistic assumptions that exaggerate the importance of robotics, by itself, in improving productivity. Two reasons are offered:

1) Robotics is only one part of a wide array of technologies available to automate manufacturing and to increase industrial productivity.
2) Productivity is a subtle and complex concept with several definitions and measurements. Furthermore, even after some specific definition is chosen, industrial productivity depends on many factors that interact with one another. Hence, it is difficult to attribute productivity improvements to any single technology.[35]

These warnings do not suggest that robotics is an unimportant technology. Most experts seem to feel that it is important. How-

ever, they state that there are dangers inherent in taking an overly narrow definition of the technology when assessing impacts on industrial productivity.

While most applications of robots to date have been made by large firms, the future diffusion of robotics and related technologies will also affect small businesses in several ways. For example, there are likely to be many new business opportunities for small firms to develop and produce software and specialized types of equipment. Second, it can be argued that robotics and flexible automation may in some cases lower the minimum scale for efficient production, and therefore that new manufacturing opportunities could be created for small businesses. Third, the adoption of robotics and related technologies by large firms may foreclose some manufacturing opportunities for small firms that cannot afford to invest in new equipment. This situation frequently arises when major equipment technologies change.[36]

Capital formation is another issue that has been raised. The important question seems to be whether there is adequate capital for three purposes:

1) To fund the modernization of industrial plants for the use of automation technology. The financial need would be particularly great if it were desired to rebuild entire plants to make the most effective use of robotics.
2) To fund the construction and expansion of plants to produce robots in quantities necessary to have a significant economic impact.

3) To fund entrepreneurs who wish to develop new types of robots for new applications. The importance of the availability of this type of capital depends on how important it is that the technology be pushed forward rapidly.[37]

The lack of capital is not an important impediment to the growth of the robotics industry or to the expansion of the use of robots in manufacturing. However, some experts believe that a tax policy that encourages such investment would be an important stimulus.

There is some disagreement about the availability of private capital to fund R & D. Robot manufacturers maintain that they have been investing large amounts of their own money in R & D. Other experts suggest that these expenditures are principally aimed at short-term product development and adapting existing products to specific tasks.[38]

ROBOT APPLICATION

Robot shipments are also classified by user. The automobile industry typically has been the primary buyer except in 1980, when the electric appliance industry, which usually occupied second place, took the lead for the first time. However the automobile industry still dominated the sphere of sophisticated robots.[39]

The large percentage of exports of playback robots compared to the less than 2% export share of total industrial robot production indicates the direction of Japan's export policy.

Since the playback robot seems to be concentrated heavily in the automotive industry, an analysis of the type work performed by playback could indicate relative use.[40]

It is clear that spot welding represents the major application of the playback robots. A preliminary report on calendar year 1980 robot production revealed that compared to 1979, arc welding robots increased 211% in value and 100% in units, and spot welding robots grew 85% and 100%, respectively. In addition, assembly robots grew 340% and 33%, respectively (certainly from a low base), and press and conveying robots 60% and 6%, respectively. The large growth in assembly robots was mainly for insertion of electronic parts into printed circuit boards (an increase of 440% in 1980 compared to 1979.[41]

SPOT WELDING

The automobile industry had until 1980 been the largest single consumer of robot production, in large measure because of its purchases of spot welding robots. The majority of Japanese car bodies consist of 300-400 press-formed parts manufactured from sheet steel, which are bonded together by 3000-4000 spot welds. In the latter half of the 1960s, special-purpose automatic multispot welding machines were introduced. However, with the tendency to produce diversification and the shorter life cycle of car models, the return on investment of the multispot welder declined. Large monetary expenditures to modify the multispot welders were necessitated by model changeover or design modification. During the modification, a considerable period of

time was lost and management expenses were consumed for production line reorganization.

Thus, the robots replaced the multispot welders because they only require being taught where to weld in the new model in the event of a model changeover. Often merely one hour is required for the new learning process. As production volume is no longer clearly predictable, it became quite risky to invest in special-purpose automatic machines. Investment in the more flexible robot seemed preferable. The robot also eliminates the need of manual operator to follow the conveyor line with a heavy welding gun.[42]

The automobile companies then introduced batteries of robot welders. In some assembly plants a single operator for robots can handle a work load once shared by ten workers. To improve productivity by simultaneous multispot welding, efforts have been made to develop multiarm welding robots and to apply a number of modular robots to welding. Robot introduction into the spot welding line has made possible the automation of multi-product mixed-flow-assembly line on which various models flow one after another.[43]

Nissan has been the largest user of spot welders and by the end of 1980, it had about three hundred spot welders. At the same time, Toyota reportedly had two hundred spot welding robots, but it ordered seven hundred and twenty robots from Kawasaki Heavy Industries--two hundred twenty by March 1981, two hundred by March 1982, and three hundred by March 1983. It has been assumed that most of these would be used for spot welding.

Kawasaki is reportedly delivering about twenty-five units monthly. Mitsubishi Motors has been receiving spot welding robots from Mitsubishi Industries. Toyo Kogyo and Honda have introduced welding robots.[44]

Kawasaki H.I. is clearly the leader in production of robot spot welders. By spring 1981, it had delivered 1500 Unimates primarily for spot welding, and its monthly production rate is sixty. Mitsubishi H.I. occupies second place, having delivered two hundred and fifty robots by the spring of 1981 and with a monthly production rate of slightly over ten. Toshiba Seiki produces a modular spot welding high-speed robot that can reach a monthly rate of thirty-five to fifty. Toyoda Machine Works is also making an inexpensive building block system spot welding playback robot, offered for public sale since the fall of 1982. Toyoda expects to sell one thousand units annually. It is not known how many of these have already been shipped to Toyota. By 1983, Toyoda Machine Works and Toshiba Seiki, if they should be successful in their modular and simpler spot welding robots, could occupy a significant market share.[45]

ARC WELDING

Arc welding operations are conducted in an extremely unfavorable environment where carbonic acid gas, fumes, and heat are generated. As a result, arc welders must wear masks and, consequently, must take time out frequently. Some loss of operating time is therefore, inevitable. In addition, the new generation of young workers, being better educated, tend to shun

arc welding. As a consequence, arc welding is particularly susceptible to robotics.[46]

However, robots such as the Kawasaki Unimate, which could handle heavy loads, could hardly be justified economically by an application that largely used lightweight welding guns. Yaskawa Electric Manufacturing, at present, dominates the arc welding robot applications with its relatively low-priced playback robot. Shinmeiwa developed arc welding robots for work on heavy plates while Osaka Transformer developed arc welding robots for work on sheets. Kobe Steel has produced a more expensive, continuous-path-control arc welding robot. Hitachi had produced two robots suitable for arc welding: a sophisticated intelligent robot and a low-priced articulated playback robot. Matsushita has introduced a very competitive arc welding robot.

With Matsushita entering the arc welding area and with Hitachi capable of substantially increasing its output, it is entirely possible that these two firms will ultimately dominate the arc welding market.[47]

SPRAY PAINTING AND COATING

Painting robots are the third largest type of playback robots and are now growing at the same rate as spot welding robots but not as fast as the arc welding robots. Spray painting and coating offer a rich area of application. To become skilled, a coating worker required two to three years of experience. However, the poor working environment and the tendency to a more

educated society contributed to a developing skilled worker shortage. The necessity for a large percentage or rework made production planning difficult.

The industrial robot provided certain advantages in painting:

1) They ensured stability of product quality and therefore made possible improved production planning and control. Despite the selection of the most skilled workmen for finish coating, the quality of the finish varied according to the workers and the conditions of the day. In automobiles, the paint finish of a car, and especially its uniformity, is a determining element in the Japanese domestic consumer preference.
2) They made possible a multiproduct mixed batch coating line.
3) They provided continuous production operation and reduced the need for intermediate stocks.
4) The manual workers and special-purpose automatic coating machines tended to increase the use of paint to preclude uneven coating, especially in complicated shapes. In addition, special-purpose automatic coating machines tend to overspray paint on smaller products in a multicoating coating line. In the case of spray painting an auto body, a savings of 10-20%

in the use of paint has been effectuated. Reducing the amount of paint reduced the need for ventilation and therefore saved on energy consumption.

5) Spray painting is a very unhealthy job because of the chemicals and dust. The spray painting robot could free the operator from staying in the spray booth. It provided a relatively simple way to meet safety regulations.[48]

Kobe Steel introduced the Norwegian Trallfa spray painters. Both Hitachi and Mitsubishi Heavy Industries worked with other firms--Nihon Parkerizing Company and Iwata Air Compressor Manufacturing Company, respectively, to develop playback spray robots. Tokico offered a large variety of low-priced painting robots, while Nachi Fujikoshi offered a spray robot with both remote and direct teaching.[49]

Considering the demand for spray robots (Nissan alone is reportedly seeking three hundred units) it seems evident that production objectives will be increased. It is still too early to predict the future market share as changes are expected shortly, at least in Hitachi.

MACHINE LOADING AND UNLOADING

Industrial robots have been applied to a wide variety of production processes in which the basic breakdown of the process

indicated that the robot is being used primarily, if not exclusively, for (1) loading and unloading, (2) transshipping, and (3) palletizing and depalletizing. This refers to applications in the following areas:

1) Die Casting
2) Forging
3) Press work
4) Plastic Molding
5) Machine Tool Loading
6) Heat Treatment

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In each production process, fierce competition exists between those who designed industrial robots, often relatively unsophisticated, for particular production processes and the universal robot makers who offer playback and intelligent robots. In most cases, however, the specialists seem to have won out as of now. In press working operation Aida Engineering seems to have won dominance though strongly challenged by Toshiba Seiki. Similarly, Fujitsu Fanuc seems to enjoy supremacy now in the loading of machine tools although Kawasaki Heavy Industries has mounted a strong challenge.[51]

In plastic molding (the automatic unloading of injection molded products) the small manufacturers dominate. Ichikoh Engineering Company and Kyoshin Electric offer a complete line of fixed sequence machines. Star Seiki offers both fixed and variable sequence robots. Sailor Pen, likewise, offers

relatively unsophisticated machines. For unloading workpieces from a die casting machine, Ichikoh offers its fixed sequence machine, while Shoku and Diado offer variable sequence robots.

For putting workpieces into a furnace Shinko Electric has a relatively sophisticated variable sequence robot. Nachi Fujikoshi offers a specially designed robot to tolerate hot temperature, which has been used to transfer workpieces from a furnace to press.

In the forging area, a great number of robot makers offer a variety of specialized products: Aida, Kobe Steel, Komatsu, and Nachi Fujikoshi.[52]

MACHINING

In Japan one operator of N.C. machine tools serves on average less than two N.C. machine tools. This low ratio is the result of manual loading and unloading of the workpieces, manual disposal of chips, and maintenance. Many Japanese firms sought robotic solutions to this problem. One of the consequences of the application of robots to machining besides improved productivity was improved production management. Robots could respond more elastically to changes in production volume, and in the event of temporary requirements for increased production, they could easily be worked overtime. Where the process was computerized, it was possible to know beforehand when a machinery operation would be completed.[53]

While several other companies manufacture robots for machining, Fujitsu Fanuc dominates this application area with an output of

one hundred units monthly. The Fanuc Model 0 uses the NC of the single machine tool which it services; the Model 1 and 2 (known in the U.S. as model 3) have their own NC service up to two and five machines, respectively. These machines make possible an unattended machining system that operates automatically at night.

The entry of Fujitsu Fanuc into robots has caused some of its competitors and some of the machine tool manufacturers to develop and produce robots of their own. This is especially true of Okuma, which supplies its own NC for its machine tools. In addition, Yamatke-Honeywell and Ikegami Iron Works have started production of NC robots. Fanuc introduced additional models in the summer of 1981.

Fanuc's competitors now are other manufacturers of robots who have modified their products to service machine tools.[54]

TRANSFERRING

Closely allied to the machine loader/unloaders are the robots engaged primarily in the transfer of materials. Many robots equipped for specialized processes such as welding and painting can also be modified for transferring materials. In addition, many conveyor equipment manufacturers were compelled to produce robots to compete with robot manufacturers entering their market. Some robot makers entered the materials-handling market trying to carve a special niche for themselves.[55]

Shinko Electric, Taiyo, and Kayaba Industry are manufacturers

of machine-loading robots that entered into the transfer field. The conveyor manufacturers that entered the field include Tsubakimoto and Sanki Engineering. The "universal robot makers" offering machines for transferring include Kawasaki, which offered modifications of its Unimate for that purpose, Daido Steel, Yasakawa, Nachi Fujikoshi, and Toyoda Machine.

Some firms specifically developed a line of materials-handling robots. Dainichi Kiko has developed a line of heavy-duty tranfer robots. Motoda (now Oriental Terminal Products) make a complete line of what is described as multipurpose versatile robots in both variable sequence and playback versions. Their major, if not exclusive market, seems to be the materials-handling area, but Motoda claims that these robots can be used for welding and spray painting. Toyo Keiki has developed a series of variable sequence robots specifically dedicated to palletizing and depalletizing. The entire area of transfer robots like the area of machine-loading robots is still too greatly splintered to provide a meaningful market share analysis.[56]

ASSEMBLY ROBOTS

Assembly robots capable of inserting, screwdriving, bonding, and similar processes exist largely either in the R & D or the early application stage in Japan. Most major electrical manufacturers, such as Hitachi, Matsushita, Mitsubishi, NEC, Oki and Fujitsu, have developed fully automatic systems for bonding. All these use cameras for visual perception to position by shape or pattern and in the case of Hitachi and Mitsubishi Electric, to

detect defects. Fuji Electrics "Checker robot," which examines and rejects pharmaceutical pills, is not a robot but does use both visual (by use of a camera) and tactile perception for quality inspection.[57]

In addition, special-purpose automatic assemblers provided considerable data for constructing assembler robots. Hitachi built for Nissan an automatic tire fitting system that uses a machine hand to detect the hub bolts, position them, and tighten them. Hitachi also developed a fully automatic system for fitting rubber belts to tape recorders from which they learned assembly principles suitable for automobile and electric applicance belt fitting.

Hitachi manufactures an intelligent robot with a twenty-five step memory capacity and a seven ounce (200-g) load capacity that can fit different components one by one in a specified order. The robot moves fast, requiring only one to two seconds to fit workpieces. Its finger support is flexible to prevent excessive force. Its positioning precision does not have too close a tolerance, but a special searching function automatically detects the holes of workpieces and fits them properly even when positioning is not accurate. An automatic rejecting function within the robot prevents assembly of defective workpieces.[58]

Both Hitachi and Matsushita have built experimental robots to assemble electric vacuums.

The larger electronic/electrical manufacturing companies are planning to robotize 50-75% of their assembly operations by 1985. This would indicate that far more activity and experi-

mentation has taken place than has so far been publicly revealed.[59]

In March 1981, Hitachi publicly announced a task force of five hundred key technology experts to fashion and install a standardized assembly robot with both visual and tactile sensors, microcomputer control, and mobility, and projected a 60% robotization of its assembly processes by 1985. In April 1981, Matsushita announced a plan to marshall the entire staff of its technological division to develop intelligent industrial robots controlled by microprocessors and modularized building block system (BBS). Matshushita revealed that some BBS robots were already functioning at its plants. The new robots were to be of three types--(1) robots that position workpieces accurately, (2) robots that assemble workpieces, and (3) robots that adjust the finished product to function as originally designed.[60]

NEC then reported that it had developed a factory robot that assembles electronic machinery and appliance parts and components with a speed of 18 in./sec (45 cm/sec) and a positioning accuracy of only 0.00032 in. (8 cm). The high precision and speed has been realized by computerization and by the application of the principle of electronic magnetic repellance, utilizing the linear-motor levitation technology that has been used by the Japanese National Railways in developing the "floating" train. The NEC linear-motor-driven robot arm and hand picks up a machine part or component with a maximum load of 4.4 lb (2 kg) and carries it around by making it float over the work table. The high precision of movement is achieved by the robot's set of sixteen sensors (visual) supported by a built-in microprocessor. NEC

has been producing these assembly robots so far for its own factories and those of affiliated companies.

In June 1981, Ishikawajima Harima Heavy Industries, a close ally of Toshiba, announced plans to produce its Group Manipulator Module System (GMMS) with an articulated arm with the most advanced parallel circuit-type 16K RAM in its microprocessor.

Fujitsu Fanuc has also developed an assembly robot. This is the much publicized robot that builds robots. Fujitsu is working closely on robot development with its affiliate.[61]

The heavy emphasis on assembly and sense perception by the private firms, universities, and public research institutes would seem to indicate the possibility of achieving the goal of popularization of assembly robots by 1985. As will be discussed later, the Japanese consider that the intelligent robot is an important element of expert policy for the future.[62]

JAMES S. ALBUS

In the United States at present, there are only about three thousand robots installed. That's less than the number of workers employed in a single factory in many companies. That's less than the graduating class of some high schools in this country. Today, there is a bigger market for toy robots than for real robots. So at least for the present, robots are having almost no effect one way or another on overall productivity in this country. Today's robots are being produced in the United States at the rate of about 1,500 per year. Predictions are that this will probably grow to between 20,000 and 60,000 robots per year by the year 1990.

In other words the production rate is growing at about a factor of 10-30 per decade. At that rate the United States will be lucky to have a million robots in operation before the year 2000. This means that unless there is some drastic change in the presently projected trends, there won't be enough robots in operation to have a significant impact on the overall productivity of the nation's economy before the turn of the century.[63]

Of course, there will be some specific areas where the impact of robots will be large. In areas like automobile spot-welding, robots have already had some effect. By the mid 1980s there may be a significant effect on productivity in arc welding.

Arc welding is a hot, dirty, unpleasant job where the welder must wear heavy protective clothing and must work in the presence of a shower of hot sparks and coking smoke. Typically a human welder cannot keep his torch on the work more than 30% of the time. A robot welder, on the other hand, can keep its torch on the work about 90% of the time. Thus, even though the robot cannot weld any faster than a human, it can turn out about three times as much work.[64]

Unfortunately, present day robots cannot set up their work. That requires a human assistant. So this reduces the productivity advantage. Also, the robot must be programmed to perform the welding task. Typically this takes much longer than would be required to actually perform a weld. Thus, unless the robot is used to perform many repetitions of the same welding task there is not productivity gain.[65]

Of course, once robots become intelligent enough to assemble and set up their own work, productivity will improve. Once robots

become clever enough to look at the job and figure out where to put the weld, productivity will improve even more. Eventually, welding robots will be sufficiently sophisticated to work from plans stored in computer memory and to correct errors that may occur during a job. Welding robots will then be able to work nights and weekend (four shifts per week) completely without human supervision. At that point productivity improvements over present methods of many hundreds of percent become possible. Unfortunately, we are a long way from that today. There are many difficult research and development problems that must be solved first. Unless the level of effort in software development is increased many fold, these improvements will not be realized for many years.

Let's look at another industry, the metal cutting industry, where robots are already being used to load and unload machine tools. This is a relatively simple task, so long as the parts are presented to the robot in a known position and orientation. During the 1980s, robot sensory and control capabilities will improve to the point where robots can find and loan unoriented parts, or in some cases, even pick parts out of a bin filled with random parts lying on top on each other. This may improve productivity by hundreds of percent because it will make it possible to install robots in many existing plants without major reengineering of production methods. For example, in conventional N.C. machine shops, a single machinist could set up several machines which could then run for extended periods unattended. In some cases robot-tended machines may run over-

night and on weekends without human intervention.[66]

By 1990 robots may begin to have a significant impact on mechanical assembly. There has been a great deal of research effort spent on robot assembly. Unfortunately, the results have not been spectacular--yet, on the other hand, robots cannot compete with so-called "hard automation" in assembly of mass-produced parts. General-purpose machines like robots are still too slow and too expensive to be economical for mass production assembly tasks. On the other hand, robots cannot yet compete with assembly workers in small lot assembly. Humans are incredibly adaptable, dexterous, as well as fast, skilled, and relatively cheap compared to robots. A human has two hands and ten fingers with arms, and shoulders mounted on a mobile platform equipped with a total of 58 degrees of freedom. The human has a fantastically sophisticated vision system and can be programmed to perform a wide variety of tasks quite easily. Even in a relatively routine task such as the assembly of an automobile alternator (performed at the C.S. Draper Lab, Cambridge, MA), test results indicated that robot assembly would only marginally be effective economically even after every phase of the task has been optimized.[67]

Nevertheless, progress is being made and will continue. Robot capabilities will gradually increase. Sensory systems will become more sophisticated and less expensive. The cost of computing hardware is dropping rapidly and steadily with no sign of bottoming out. Software costs are likely to be the major impediment to robot development for the foreseeable future, but

even these are slowly yielding to the techniques of structured programming and high level languages.[68]

Eventually, extremely fast, accurate, dexterous robots will be programmed using design graphics data bases which describe the parts to be made and the configuration of the assemblies to be constructed. Eventually, robots will be able to respond to a wide variety of sensory cues, to learn by experience and to acquire skills by self optimzation. Such skills can then be transferred to other robots so that learning can be propagated rapidly throughout the robot labor force.

During the 1990s robots will probably enter the construction trades. Under the tutelage of a human master-craftsman, apprentice robots will carry building materials, life and position wall and floor panels, cut boards to size, and lay brick, block, and eventually stone. In the next century, labor-intensive building techniques (using robot labor) may once again become practical. Homes, streets, bridges, gardens, and fountains may be constructed of sculptured stone, quarried, cut, and assembled by robots. Eventually, robots will mine the seabed, and farm the surfaces of the oceans for food and fuel. And, of course, robots will play a major role in outer space - in the construction of large space structures, in space manufacturing, and in planetary exploration.

Robot technology will develop to the degree necessary to produce the totally automated factory. In such factories robots will peform most, if not all, of the operations that now require human skills. There will be totally automatic inventory and tool management, automatic machining, assembly, finishing, and

inspection systems. Automatic factories will even be able to reproduce themselves. That is, automatic factories will make the components for other automatic factories.

Once this occurs, productivity improvements will propagate from generation to generation. Each generation of machines will produce machines less expensive and more sophisticated than themselves. This will bring about an exponential decline in the cost of robots and automatic factories which may equal the cost/performance record of the computer industry. For the past thirty years computing costs have spiraled downward by 20% per year. This, at least in part, is due to the fact that computers are used to design, construct, and test other computers. Once automatic factories begin to manufacture the components for automatic factories, the cost of manufacturing equipment will also fall exponentially. This, obviously, will reduce the cost of goods produced in the automatic factories. Eventually, products produced in automatic factories may cost only slightly more than the raw materials and energy from which they are made.

The long-range potential of totally automated manufacturing is literally beyond our capacity to predict. It may change every aspect of industrial society. Automatic factories that can operate without human labor, and reproduce themselves, could lead to an entirely new era in the history of civilization.

Now, in the light of the unprecedented economic potential of robots, I suppose I should comment on why the implementation of this technology is proceeding so slowly.[69]

First, at least in the United States, funding for robotics

R & D has been very modest. Every indication is that in the future, support will grow, but not dramatically. Certainly, there is nothing to suggest that a crash development program on the scale of the Manhattan Project or the Apollo Moon Program is imminent. Certainly, there are no plans for the federal government to launch such an effort, and private investment funds are not likely to be committed on a massive scale because of the long time to pay back. Robotics is still a long term research topic. We are a long, long way from a sophisticated sensory interactive, intelligent, highly skilled, dexterous, economically feasible, and commercially manufacturable robot. Research in this area is long term, time consuming, and risky. Also, there is no certainty that inventions can be kept proprietary. There is, therefore, no guarantee that the firms that make the investment can capture enough of the benefits to make the risk worthwhile.[70]

Secondly, even after the research and development problems are solved, several decades and many hundreds of billions of dollars will be required to convert the present industrial base to robot technology. This enormous investment will severly tax available sources of capital. This transformation of the entire industrial plant of a country simply cannot be achieved except over an extended time period.

Thirdly, and perhaps most importantly, many voters question the desirability of rapid, massive deployment of robot technology. Despite the obvious benefits from productivity improvement, there would be serious social and economic adjustments necessary as a

result of such a rapid productivity growth. Productivity improvements by its very nature reduces the amount of human labor needed to produce a given product. Thus, an obvious, but I believe incorrect, conclusion is that a rapid increase in productivity would lead to unemployment. There is a widespread perception that robots pose a threat to jobs. The fear is that if robots were introduced at the rate that is technologically possible, unemployment would become a serious problem.

However, widespread unemployment is not the inevitable result of rapid productivity growth. There is not a fixed amount of work. More work can always be created. All that is needed is a way to meet the payroll. Markets are not saturated. The purchasing power of consumers can always be increased at the same rate that more products flow out of the robot factories. At present, there is plenty of demand. The mere fact of inflation is prima facie evidence that consumer demand exceeds the ability of present production techniques and facilities to supply goods and services at constant prices. Work is easy to create. So is demand. What is hard to produce is goods and services that can be sold for a profit, at (or below) the current market price.

Nevertheless, the average citizen is unconvinced that advanced automation would necessarily put increased spending power into his or her pocketbook. The question is--If the robots have most of the jobs, how will average people get their income? In order for most people to be convinced that robots are going to bring more benefits than problems, it will be necessary to demostrate that a variety of alternative income producing occupations

will be created to fill the void left by those jobs which are taken over by robots. Fortunately, this is not difficult to do.[71]

Perhaps, the most obvious source of new jobs is in the industries that must be created in order to convert to a robot-based economy. Certainly if quantities to make significant impact on the existing industrial system, entirely new robot manufacturing, sales, and service industries will emerge and millions of exciting new jobs will be created. A typical industrial robot costs from $30,000 to $80,000 and sometimes more by the time it is installed and operating. This means that every robot installed creates two to four person-years of work somewhere in the economy. The robot market is presently growing at about 35% per year, which means it doubles about every three years. As long as this growth rate continues, robot production will add jobs to the economy about as fast as robot installation takes them away.[72]

It will be many years, perhaps many decades, before robots can design, manufacture, market, install, program, and repair themselves with little or no human intervention. In the meantime, the manufacture and servicing of robots will produce an enormous demand for mechanical engineers, technicians, computer programmers, electronic designers, and robot installation and repair persons. New robot companies will require secretaries, sales persons, accountants, and business managers. It seems likely that the robot industry will eventually employ at least as many people as the computer and automobile industries do today.

Converting the world's existing industrial plants from manual

to robot labor will require many decades and will cost as much as the total existing stock of industrial wealth. This is a Herculean task which will provide employment to millions of workers for several generations. For a country like the United States which has a strong technological base, the world market in robots could easily create twice as many jobs in robot production as were lost to robot labor. Needless to say, the export of robot systems (as well as products made by them) could have a strong positive effect on the balance of trade and the strength of the dollar on the international market.

In general, industries that use the most efficient production techniques grow and prosper, and hire more workers. Markets for their products expand and they diversify into new product lines. Workers displaced by automation are simply transferred into new growth areas or retrained for different occupations. It is in the industries that fall behind in productivity that job layoffs are prevalent. Inefficient industries lose market-share to competitors, shrink, and eventually die. Thus, the biggest threat to jobs is not in industries that adopt the latest robot technology, but in those which do not.

For example, there are almost one-half million jobless workers today in the American automobile industry. This is not because of a couple thousand robots. It is because of the energy crisis and because of foreign competion. U.S. auto workers are suffering unemployment more because of robots in Japan than because of robots in Detroit. If America continues the present low rate of productivity growth, we cannot help but

have even greater unemployment. Foreign trading partners are modernizing at a rapid rate. If we do not innovate, our products cannot compete, and our workers will find their jobs being taken away by foreign competition.[73]

Improving productivity is not easy. It requires research, development, education, capital investment, and incentives to do better. The technology of advanced automation is not a quick fix. It is a long-range solution. Robots have much promise but a long way to go. We are only beginning to understand some of the technical problems. We are many years, perhaps several decades, from making truly intelligent, highly skilled robots. But technical solutions will come. It is only a matter of time, money, and intellectual resources. The real question is whether we can evolve a society in which robots will complement, not compete with humans for their livelihood. If this problem can be solved, then the prospects for the future may be very bright indeed. Robots and automatic factories have the potential to increase productivity virtually without limit. This potential, if brought to reality, could create a material abundance and standard of living that far exceeds the horizon of today's expections. Over the next two centuries the technology of robotics and advanced automation could make everyone rich. Robots someday could provide the economic foundation for an "every person's aristocracy." However, this will require that we find a way to make them work for us, and not in competition with us. To protect the human worker's livelihood in the coming decades there are several steps which can and should be taken.[74]

First, we must provide retraining for workers displaced by robots for new and better occupations.

Second (after a decade or so when robots begin to make a significant impact on productivity), we can decrease the work-week. It is nowhere written in stone that humans must work forty hours per week. As robots take over more and more work, humans can improve their work environment and decrease their work periods to thirty, twenty or even ten hours per week. Education and leisure activities can be increased virtually without limit. Eventually all "work" could be voluntary.

However, in order to achieve this we will need to explore a wide variety of mechanisms for broadening our ownership of robots and automatic factories. Employee stock ownership plans, individual robot-owner enterpreneurs, and even semi-public mutual fund ownership plans might be developed in the future. If everyone could own the equivalent of one or two robots, everyone would be financially independent, regardless of whether they were employed or not.

Finally, in the next few years and decades, we must recognize that it is premature to worry about insufficent work to go around. There is virtually an unlimited amount of work that needs to be done in eliminating poverty, hunger, and disease, not only in America, but throughout the world. We need to develop renewable energy resources, clean up the environment, rebuild our cities, exploit the oceans, explore the planets, and colonize outer space. The new age of robotics will open many new possibilities. What we humans can do in the future is limited only by our imagination to see the opportunities and our courage to act out our beliefs.[75]

END NOTES

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[2]Ibid., p. 3.

[3]Ibid., p. 39.

[4]Ibid., p. 40.

[5]Ibid., p. 40.

[6]Ibid., p. 40.

[7]Ibid., p. 41.

[8]Ibid., p. 41.

[9]Ibid., p. 41.

[10]Ibid., p. 41.

[11]Ibid., p. 41.

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[15]Ibid., p. 43.

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[18]Hunt, Daniel V. Industrial Robotics Handbook. (New York: Industrial Press Inc., 1983), p. 150.

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[20]Ibid., p. 152.

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[60]Ibid., p. 310.

[61]Ibid., p. 310.

[62]Ibid., p. 311.

[63]Ibid., p. 351.

[64]Ibid., p. 351.

[65]Ibid., p. 352.

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